

Elastic parton scattering and non-statistical event-by-event mean- p_t fluctuations in Au + Au collisions at RHIC

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Non-statistical event-by-event mean- p_t fluctuations in Au + Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV are analyzed in AMPT with string-melting, and the results are compared with STAR data. The analysis suggests that in-medium elastic parton scattering may contribute greatly to the mean- p_t fluctuations in relativistic heavy-ion collisions. Furthermore, it is demonstrated that non-statistical event-by-event mean- p_t fluctuations can be used to probe the initial partonic dynamics in these collisions. The comparison shows that with an in-medium elastic parton scattering cross section $\sigma_p = 10$ mb, AMPT with string-melting can well reproduce $\sqrt{s_{NN}} = 130$ GeV data on the centrality dependence of non-statistical event-by-event mean- p_t fluctuations. The comparison also shows that the fluctuation data for $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions can be well reproduced with σ_p between 6 and 10 mb.

PACS numbers: 25. 75. -q, 25. 75. Gz

I. INTRODUCTION

In order to detect the production and to study the properties of Quark-Gluon-Plasma(QGP), non-statistical event-by-event mean- p_t fluctuations in relativistic heavy-ion collisions have been measured[1, 2, 3, 4, 5, 6] at CERN SPS and BNL RHIC, and have been extensively studied theoretically[7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 21]. While experimental data show that a strongly interacting quark-gluon-plasma(sQGP) has been produced in heavy-ion collisions at RHIC [22, 23], a common consensus on the explanation for the data on non-statistical event-by-event mean- p_t fluctuations measured at RHIC has not been reached yet[4, 5, 6, 15, 16, 17, 18, 19]. To be more specific, the observed non-statistical event-by-event mean- p_t fluctuations at RHIC currently can be explained in various physical scenarios: quenched jets/minijets production [5, 15], a large degree of thermalization[16], percolation of strings[17], a build-up of radial collective flow [18] and formation of "lumped clusters" [19, 20]. Though jets/minijets contribute significantly to the event-by-event mean- p_t fluctuations[19] and jet-quenching reduces the fluctuations[5], as HIJING model[24] predicts[15], HIJING model significantly underestimates the STAR data[4, 6] on the event-by-event mean- p_t fluctuations. This may imply sources of the mean- p_t fluctuations beyond jets/minijets production. Taking into account the fact that HIJING model includes neither partonic nor hadronic cascade processes, one may wonder if the HIJING-based AMPT model[25, 26], which includes parton cascade together with hadronic cascade processes, is able to reproduce the STAR data on non-statistical event-by-event mean- p_t fluctuations. Additionally, how partonic and hadronic cascade processes contribute to the non-statistical event-by-event mean- p_t fluctuations is an interesting question in heavy-ion collisions at RHIC

energies[15]. The intention of this letter is to answer these questions.

II. THE AMPT MODEL AND ANALYSIS METHODS

The AMPT model is a hybrid model. It uses minijet partons from hard processes and strings from soft processes in HIJING as the initial conditions for modeling heavy ion collisions at ultra-relativistic energies. Since a phase transition of hadronic matter to quark-gluon plasma would occur [27, 28] in Au + Au collisions at RHIC, we study partonic effects on event-by-event mean p_t fluctuations using the AMPT model which allows the melting of the initial excited strings into partons[29]. Interactions among these partons are described by the ZPC parton cascade model[30]. At present, the AMPT model includes only parton-parton elastic scatterings with an in-medium cross section given by:

$$\sigma_p \approx \frac{9\pi\alpha_s^2}{2\mu^2}, \quad (1)$$

where the strong coupling constant α_s is taken to be 0.47. The effective screening mass μ is generated by medium effects and given as an adjustable parameter thus it can be used in studying effects of parton scattering cross sections in heavy-ion collisions. The transition from the partonic matter to the hadronic matter is achieved using a simple coalescence model[26]. Following the formation of hadrons, hadronic scatterings are then modeled by a relativistic transport (ART) model [31]. This version of the AMPT model is able to reproduce both the centrality and transverse momentum (below 2 GeV/c) dependence of the elliptic flow [29] and pion interferometry [32] measured in Au + Au collisions at RHIC [33, 34]. It has been also applied for studying kaon interferometry[35],

charm flow[36], ϕ meson flow[37] and the system size dependence of elliptic flow[38].

In this letter, $\Delta\sigma_{p_t:n}$ [4] and $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ [6] are used in our analysis of event-by-event mean- p_t fluctuations. According to Ref. [4, 6], they are defined as:

$$\Delta\sigma_{p_t:n} = \frac{\Delta\sigma_{p_t:n}^2}{2\sigma_{\hat{p}_t}}, \quad (2)$$

$$\langle\Delta p_{t,i}\Delta p_{t,j}\rangle = \frac{1}{\epsilon} \sum_{k=1}^{\epsilon} \frac{C_k}{n_k(n_k-1)}, \quad (3)$$

where

$$\Delta\sigma_{p_t:n}^2 = \frac{1}{\epsilon} \sum_{k=1}^{\epsilon} n_k [\langle p_t \rangle_k - \hat{p}_t]^2 - \sigma_{\hat{p}_t}^2, \quad (4)$$

$$C_k = \sum_{i=1}^{n_k} \sum_{j=1, i \neq j}^{n_k} (p_{t,i} - \langle p_t \rangle) (p_{t,j} - \langle p_t \rangle), \quad (5)$$

and ϵ is the number of events, n_k is the number of particles in the k^{th} event, \hat{p}_t and $\sigma_{\hat{p}_t}$ are the mean and variance of the inclusive transverse momentum distribution. $\langle p_t \rangle_k$ is the average transverse momentum for the k th event defined as

$$\langle p_t \rangle_k = \left(\sum_{i=1}^{n_k} p_{t,i} \right) / n_k, \quad (6)$$

where $p_{t,i}$ is the transverse momentum of the i^{th} particle in that event. $\langle p_t \rangle$ denotes the mean of the $\langle p_t \rangle$ distribution and is given by

$$\langle p_t \rangle = \left(\sum_{k=1}^{\epsilon} \langle p_t \rangle_k \right) / \epsilon. \quad (7)$$

As pointed out in Ref. [4, 6, 20], both $\Delta\sigma_{p_t:n}$ and $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$, together with other event-by-event mean- p_t fluctuation measures, such as F_{p_t} [5] and Φ_{p_t} [7], are by definition determined by two-particle transverse momentum correlations. When only statistical event-by-event mean- p_t fluctuations exist, there are no two-particle transverse momentum correlations, hence a null value would be obtained for $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ and $\Delta\sigma_{p_t:n}$. For more details regarding the two measures, interested readers are referred to Ref. [4, 6, 11, 13].

III. SOURCES OF NON-STATISTICAL EVENT-BY-EVENT MEAN- p_t FLUCTUATIONS

Particle production in ultra-relativistic heavy-ion collisions involve the following stages: the initial stage, where jets/minijets are produced followed by partonic interactions resulting in the formation of a partonic medium

even quark-gluon-plasma; then the partonic medium undergoes hadronization to become hadrons; what follows is a hadronic stage when the hadrons may decay or interact with each other experiencing hadronic cascade until freeze-out to produce final state particles. With AMPT, the following three classes of AMPT events may be generated: class I—events with both partonic interactions and hadronic cascade process, class II—events with partonic interactions but without hadronic cascade process, class III—events with neither partonic interactions nor hadronic cascade process. Events of class III are primarily HIJING events with jet production but without jet quenching. Therefore, through analyzing non-statistical event-by-event mean- p_t fluctuations in the aforementioned three classes of AMPT events, one can study how the non-statistical event-by-event mean- p_t fluctuations are built up through aforementioned stages of particle production processes. In another word, using AMPT, one can learn to what extent jets/minijets, partonic interactions and hadronic cascade process contribute to the event-by-event mean- p_t fluctuations.

We have generated events of those three classes for Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV with impact parameter of $5 < b < 7$ fm, and analyzed non-statistical event-by-event mean- p_t fluctuations in each of the three classes of events for charged hadrons. The results are tabulated in Table. I. From Table. I, one can see, first of all, that in events of class III, there exist noticeable non-statistical event-by-event mean- p_t fluctuations due to production of jets/minijets[15]. It is noted that the values of the a and b parameter for string fragmentation used in AMPT[26] is different from those in the HIJING model. This is why \bar{n} for events of class III is greater than that from HIJING without jet-quenching. Secondly, the magnitude of $\Delta\sigma_{p_t:n}$ in events of class II is more than two times the magnitude of $\Delta\sigma_{p_t:n}$ in events of class III, and so is the magnitude of $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$. This indicates that

TABLE I: $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle(\text{MeV/c})^2$, together with $\Delta\sigma_{p_t:n}(\text{MeV/c})$ as well as the total number of events(ϵ), the mean (\hat{p}_t) and variance ($\sigma_{\hat{p}_t}$) of inclusive transverse momentum distributions, the mean (\bar{n}) and variance (σ_n) of multiplicity distributions, in-medium elastic parton scattering cross section(σ_p) for four classes of mid-central AMPT events($5 < b < 7\text{fm}$)—Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV. Except for σ_p and ϵ , these quantities are calculated using charged hadrons with $|\eta| < 1$ and $0.15 < p_t < 2$ GeV/c. Errors are statistical only.

event class	I	II	III	IV
$\sigma_p(\text{mb})$	10	10	N/A	3
ϵ	50,686	50,480	45,000	31,981
\bar{n}	600	607	765	616
σ_n	90	90	122	90
$\hat{p}_t(\text{MeV/c})$	479	477	458	457
$\sigma_{\hat{p}_t}(\text{MeV/c})$	285	276	263	275
$\Delta\sigma_{p_t:n}$	70.3 ± 1.3	79.9 ± 1.4	29.7 ± 1.1	31.7 ± 1.4
$\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$	68.5 ± 1.3	73.9 ± 1.3	21.1 ± 0.8	29.0 ± 1.2

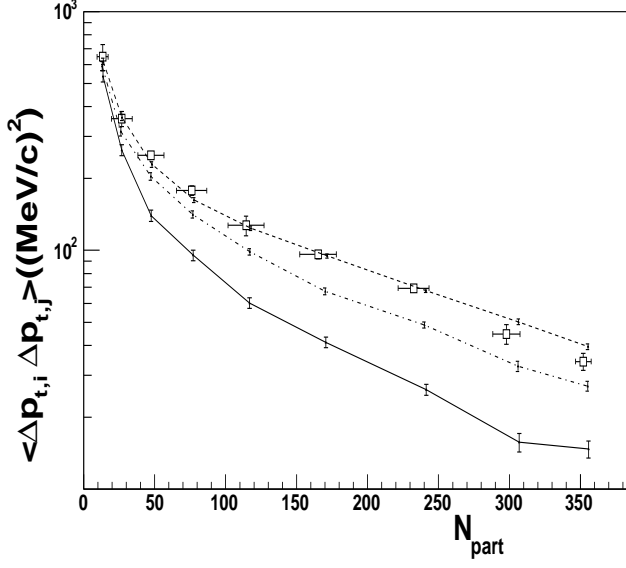


FIG. 1: (Color online) $\langle \Delta p_{t,i} \Delta p_{t,j} \rangle$ in AMPT for $\sigma_p = 10$ mb (dashed line), $\sigma_p = 6$ mb (dash-dotted line) and $\sigma_p = 3$ mb (solid line) as a function of centrality for $\sqrt{s_{NN}} = 130$ GeV Au + Au collisions compared with STAR data (hollowed squares) as reported in Ref. [6].

in addition to the production of jets/minijets of partons, elastic parton scatterings add significantly to the non-statistical event-by-event mean- p_t fluctuations. Hence elastic parton scatterings may well be among others a major source of the non-statistical event-by-event mean- p_t fluctuations. Thirdly, comparing the magnitudes of $\Delta\sigma_{p_t:n}$ and $\langle \Delta p_{t,i} \Delta p_{t,j} \rangle$ for event class-I with those for class-II, one notices that due to hadronic cascade processes, the non-statistical event-by-event mean- p_t fluctuations built up in the initial stage, which is characterized by the production of jets/minijets and parton scatterings, decrease about 12% and 7% for $\Delta\sigma_{p_t:n}$ and $\langle \Delta p_{t,i} \Delta p_{t,j} \rangle$, respectively. This reduction of the mean- p_t fluctuations is an indication that the late stage hadronic cascade processes that follow the elastic parton scatterings dilute the correlations established in the initial stage. Therefore, one may conclude according to Table. I that in heavy-ion collisions at RHIC, non-statistical event-by-event mean- p_t fluctuations are generated in the initial stage; in addition to the production of jets/minijets of partons, elastic parton scatterings also contribute a large portion of the non-statistical event-by-event mean- p_t fluctuations.

IV. NON-STATISTICAL EVENT-BY-EVENT MEAN- p_t FLUCTUATIONS AND σ_p

Taking place in the initial stage of ultra-relativistic heavy-ion collisions, in-medium partonic interactions help drive the colliding system toward the formation of QGP. In addition, considering the possible modification of partonic interactions in the partonic medium, the

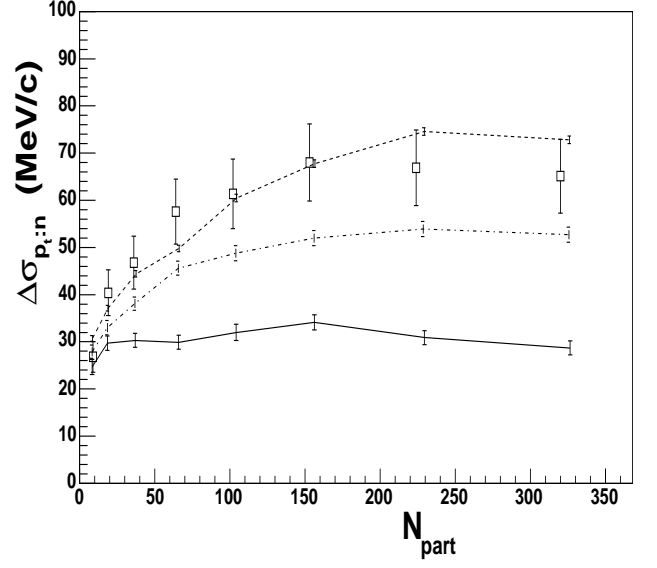


FIG. 2: (Color online) $\Delta\sigma_{p_t:n}$ as a function of centrality for Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV. The dashed line, dash-dotted line and solid line with error bars display AMPT results for $\sigma_p = 10$ mb, $\sigma_p = 6$ mb and $\sigma_p = 3$ mb. STAR data (hollowed squares) are as reported in Ref. [4], being obtained via extrapolating to 100% tracking efficiency with the error bars representing $\pm 12\%$ uncertainties.

in-medium parton scattering cross section incorporates properties of the medium and thus represents an important aspect of partonic dynamics. To study the correlation between in-medium elastic parton scattering cross section and non-statistical event-by-event mean- p_t fluctuations, in Table. I we have tabulated our results for AMPT events with in-medium elastic parton scattering cross sections $\sigma_p = 10$ mb, $\sigma_p = 3$ mb. Comparing the magnitude of $\Delta\sigma_{p_t}$ as well as $\langle \Delta p_{t,i} \Delta p_{t,j} \rangle$ calculated using $\sigma_p = 10$ mb with that using $\sigma_p = 3$ mb as tabulated in Table. I, one may come to the conclusion that non-statistical event-by-event mean- p_t fluctuations increase significantly with the increase of σ_p . This clearly indicates that the event-by-event mean- p_t fluctuations as measured with $\Delta\sigma_{p_t}$ or $\langle \Delta p_{t,i} \Delta p_{t,j} \rangle$, are rather sensitive to the in-medium elastic parton scattering cross section, and therefore are promising probes of the partonic dynamics in the initial stage of ultra-relativistic heavy ion collisions.

To estimate the in-medium elastic parton scattering cross section σ_p and to test the AMPT model with string melting, we studied the centrality dependence of non-statistical event-by-event mean- p_t fluctuations in Au + Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV based on AMPT. The results are compared with STAR data as is shown in Fig. 1, Fig. 2 and Fig. 3. In getting the AMPT results shown in Fig. 1, Fig. 2 and Fig. 3, charged hadrons with transverse momentum $0.15 \leq p_t \leq 2.0$ GeV/c and pseudo-rapidity $|\eta| < 1.0$ are used, the same cuts employed in obtaining the STAR data shown

in these figures[4, 6]. In calculating AMPT results for $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ shown in Fig. 1 and Fig. 3, the variation of $\langle\langle p_t\rangle\rangle$ within a given centrality bin is treated in the same way as Ref. [6] adopted to get the STAR data: $\langle\langle p_t\rangle\rangle$ is calculated as a function of N_{ch} , the multiplicity used to define the centrality bin. Then this dependence is fitted and the fit is used in Eq. 5 on an event-by-event basis as a function of N_{ch} . Statistical errors for AMPT results are shown in Fig. 1 through Fig. 3.

Both Fig. 1 and Fig. 2 demonstrate that with an elastic parton scattering cross section $\sigma_p = 10$ mb the AMPT model with string-melting can reproduce STAR data on the centrality dependence of the non-statistical event-by-event mean- p_t fluctuations. This conclusion is consistent with the one drawn through interferometry study of Au + Au collisions at the same energy[32, 35]. Fig. 1 and Fig. 2 also reveal that for $\sigma_p = 3$ mb the AMPT model significantly underestimates the data for non-peripheral collisions. For the most peripheral collisions, Fig. 1 through Fig. 3 display good agreement between the data and the AMPT model calculations with $\sigma_p = 6$ mb and 10 mb. That weak dependence on elastic parton scattering cross section σ_p exists because in these peripheral collisions elastic parton scatterings contribute trivially to the mean- p_t fluctuations due to a very low parton density in these collisions. From Fig. 3, one may infer that for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the STAR data can also be well reproduced by the AMPT model and support an estimate of σ_p to be between 6 and 10 mb.

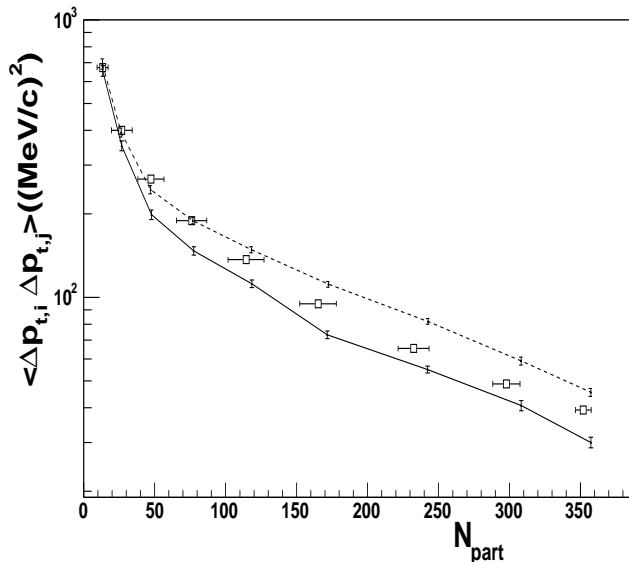


FIG. 3: (Color online) $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ in AMPT for both $\sigma_p = 10$ mb(dashed line) and $\sigma_p = 6$ mb(solid line) as a function of centrality for $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions compared with STAR data (hollowed squares) as reported in Ref. [6].

V. DISCUSSION

Jet/minijet partons may lose energy when passing through partonic medium. This parton energy loss called jet-quenching usually consists of two parts: collisional energy loss and radiational energy loss. The parton energy loss is modeled in the AMPT, as pointed out in Ref. [26], via elastic two-body parton scatterings. However in this treatment, the radiational energy loss is ignored. Looking at the AMPT results listed in Table. I, by comparing $\langle\Delta p_{t,i}\Delta p_{t,j}\rangle$ and $\Delta\sigma_{p_t:n}$ from events of class II with elastic parton scattering to those of class III without elastic parton scattering, we find that the elastic two-body parton scattering, while adding to collisional parton energy loss, gives an additional event-by-event mean- p_t fluctuations in mid-central collisions. In the following a possible explanation is given for this result. First, based on the AMPT model, parton cascade process due to elastic parton scattering is proposed to be a mechanism[39, 40] for producing a Mach-like cone structure, which has recently been observed in Au + Au collisions at RHIC[41] and has been studied in several physical scenarios[39, 40, 42, 43, 44, 45, 46, 47, 48, 49, 50]. Secondly, the Mach-like cone structure consists of clusters of final state charged particles and each of the cluster is consistent with conic emission of particles from jets, in this sense it is jet-like and its formation represents an increase of the number of jet-like clusters. Thirdly, in a recent study based AMPT, the number of correlated final state charged particles within the clusters of the Mach-like cone structure is reported to increase with σ_p changing from 3 mb to 10 mb[40]. Furthermore, stronger parton cascade due to greater σ_p also increases the number of correlated hadrons on the near-side of an energetic particle as one may infer according to Ref. [40]. To be brief, an energetic parton through successive elastic collisions with surrounding medium may couple many partons together therefore more partons are correlated with the increase of parton scattering cross section. Besides, according to Ref. [19, 20], the event-by-event mean- p_t fluctuations would increase with both the number of clusters and the number of charged particles in the clusters. Since a larger σ_p increases both the number of jet-like clusters and the number of charged particles in the jet-like clusters, it is natural that the event-by-event mean- p_t fluctuations becomes greater with σ_p changing from 3 mb to 10 mb as seen in Table. I and in Fig. 1 through Fig. 3.

Now we turn to the other energy loss mechanism, the radiational energy loss. A study by PHENIX Collaboration at RHIC and a study based on HIJING support the idea that parton energy loss tends to decrease the mean- p_t fluctuations at RHIC[5, 15]. In the HIJING model, the jet-quenching mechanism includes only radiational parton energy loss. Therefore it seems that the radiational parton energy loss causes the decrease of the mean- p_t fluctuations. Nevertheless, it would be worthwhile to investigate and compare the two mechanisms of the parton energy loss, namely, the collisional energy loss and the ra-

diational energy loss, and their implementation in both AMPT and HIJING more thoroughly before making final conclusions about the effect of parton energy loss on the mean- p_t fluctuations in heavy-ion collisions at RHIC.

VI. SUMMARY

Based on AMPT model with string-melting an analysis of non-statistical event-by-event mean- p_t fluctuations in Au + Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV is presented. The analysis suggests that in-medium elastic parton scatterings can contribute significantly to the mean- p_t fluctuations and the mean- p_t fluctuations can be used as good probes to study the initial partonic dynamics in these collisions. The AMPT results are compared with STAR data. This comparison shows that using an in-medium elastic parton scattering cross section $\sigma_p = 10$

mb, predictions of the AMPT model are in good agreement with the $\sqrt{s_{NN}} = 130$ data on the centrality dependence of non-statistical event-by-event mean- p_t fluctuations. The comparison also shows that to reproduce the mean- p_t fluctuation data at $\sqrt{s_{NN}} = 200$ GeV, σ_p is approximately between 6 and 10 mb.

Acknowledgments

We acknowledge Professor C.M. Ko, Z.W. Lin, B. Zhang, B.A. Li for using their AMPT code. We appreciate helpful discussions with Professors C.M. Ko and T.A. Trainor. This work is partly supported by National Natural Science Foundation of China(Wei-Qin Zhao); SRF for ROCS, SEM; Beijing Institute of Petro-chemical Technology and Supercomputing Center, CNIC, CAS.

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